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# CHARACTERISTICS OF THE EFFECT OF ALUMINUM ON THE MECHANICAL PROPERTIES OF TITANIUM

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16. Abstract
Aluminum, when alloyed with titanium semifinished products, is distributed unevenly in the structure, due to its solution in the α-phase. The changes in the mechanical properties of titanium occur, apparently, not only because of elastic distortions, introduced into the titanium lattice by aluminum atoms, but also due to the appearance of a second phase. The inhomogeneity of aluminum causes it to concentrate in separate microvolumes, and this is sufficient for a second phase to occur, although this $\alpha_2$-phase only occurs with an aluminum content of 7.5%.


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# CHARACTERISTICS OF THE EFFECT OF ALUMINUM ON THE MECHANICAL PROPERTIES OF TITANIUM

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At the present time, the Ti-Al system is the basic one for producing all types of titanium alloys. Therefore, a great number of works [1-9] have been devoted to research into the composition diagram of Ti-Al, and the study of the effect of aluminum on the mechanical properties of titanium. By examining the effect of aluminum on the mechanical properties of titanium, authors [1, 2, 4, 5], for the most part, believe that aluminum considerably increases the strength of titanium and simultaneously reduces its plasticity and ductility. According to information [2], alloys containing more than 7% Al have very low plasticity, and with an aluminum content of 9-10%, brittle fracture occurs, which authors explain by the appearance of a brittle $\alpha_2$-phase in the structure. In works [3, 6] the authors observed a slight increase in the relative elongation when introducing 8% Al, which was not explained. However, information in literature is devoted to the research of the mechanical properties of alloys in the Ti-Al system, and concerns the period from 1951 to 1963, when titanium sponge was produced containing a larger amount of interstitial impurities than in recent years. The use of purer sponges can cause different phase ratios in alloys [4]. Therefore, this work once more investigated the effect of aluminum on the mechanical properties of titanium when melting soft titanium sponge ingots. To achieve the best overall results, research was conducted on three batches of rods whose chemical composition, grain size, and annealing temperature are shown in Table 1. /109*

Figure 1, a shows the change in ultimate strength, relative elongation and relative reduction, depending on the aluminum content in the alloy. Here, the increase in the ultimate strength

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*Numbers in the margin indicate pagination in the foreign text.

TABLE 1. CHEMICAL COMPOSITION, ANNEALING TEMPERATURE AND GRAIN SIZE.

| Aluminum Content, % | °C | Grain Diameter, % |
|---|---|---|
| Batch I | | |
| 0 | 790 | 0.4—0.8 |
| 1,8 | 880 | 0.05—0.12 |
| 3.6 | 880 | 0,05—0,1 |
| 4.6 | 890 | — |
| 5.6 | 890 | — |
| 7.5 | 900 | — |
| 9.15 | 910 | — |
| Batch II | | |
| 0 | 780 | 0.08—0.13 |
| 1.46 | 850 | 0,05—0.12 |
| 3,42 | 880 | 0,05—0,18 |
| 5.75 | 900 | — |
| 8,00 | 920 | — |
| Batch III | | |
| 0 | 780 | 0,10—0,15 |
| 1.78 | 850 | 0,05—0,10 |
| 3.94 | 880 | — |
| 6,07 | 900 | — |
| 7,6 | 920 | 0,07—0,12 |

is shown in the form of the dependence of absolute differences of values of the ultimate strength of alloys and pure titanium on the content of aluminum. Figure 1, a shows that the increase in strength properties of alloys with an increased aluminum content does not /110 occur straightforwardly -- a recurvature is observed in melts II and III groups in concentration intervals ~ from 4.5 to 6.0% Al. When there is a 9.77% content of Al, specimens undergo brittle failure. The relative reduction of unalloyed titanium was 70-80%. The introduction of 2% Al causes a sharp reduction of relative reduction. When the aluminum content is increased from 2 to 4%, there is only a small decrease of the relative reduction. In concentration ranges from 5 to 8% Al, the ultimate plasticity of alloys hardly changes, and with a further increase in aluminum content (from 9 to 10%), it is reduced to 0-9%. Other characteristics of plasticity change similarly: the relative elongation, the maximum depth of deflection when puncturing an Ericsen sample, and the value of compressive strain when testing for swaging (Fig. 1, b). However, as opposed to relative reduction, these plasticity characteristics increase abnormally in alloys with an aluminum content of 7-8%.

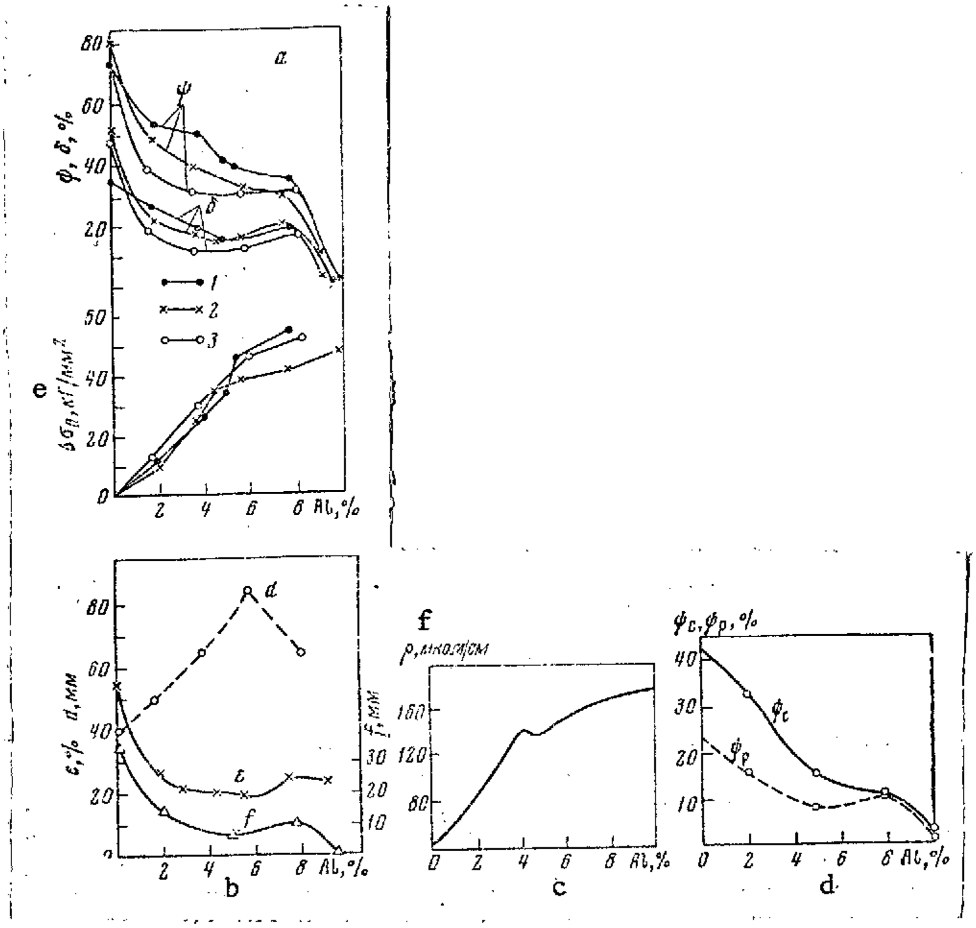


Fig. 1. The effect of aluminum on the mechanical properties of titanium (a); compressive strain when testing for swaging ε, the deflection value of the plate when testing for static depression f, and the value of the critical mandrel diameter when testing a wide sample for deflection d (b); electric resistance (c), and the change in uniform and concentrated waste (d).
1 - group I alloys; 2 - group II alloys; 3 - group III alloys.

Key: e. $kgf/mm^2$
f. μΩ/cm

The critical mandrel diameter also increases when the aluminum content is increased to 5.75%, and again decreases when the aluminum content is 8.4% (see Fig. 1, b). By comparing the properties of a number of single-phase titanium alloys, one notices that a sharp reduction of plasticity characteristics only occurs when aluminum is introduced (Table 2). Alloys separately alloyed with 1.6% Al, 5% Zr, 4% Sn or 1% V have approximately identical yield limits, and the plastic characteristics of titanium are sharply reduced when introducing 1.6% Al, whereas the plasticity for the remaining alloys either changes little (alloyed with vanadium, zirconium), or is reduced by a lesser degree than when adding aluminum (alloyed with tin). The structure of these alloys was examined with an /111
optical microscope; it was practically uniform and consisted of polyhedral α-phase grains. Even cold deformed industrial titanium (50% deformation) has a greater reserve of plasticity than a titanium alloy with 3.42% Al with practically the same yield limit (Table 3).

By reviewing these results, one can conclude that the uniformity of change of plasticity characteristics and strength of titanium when it is alloyed with aluminum has at least three features which need explanation: 1) a sharp reduction of plasticity when there are small concentrations of Al (up to 2%); 2) a recurvature on concentration strength curves with a content of approximately 5% Al; 3) an increase in plasticity (apart from compressive strain) with aluminum contents of 7–8%.

Additional research was conducted, including metallographic, resistometric and local micro-x-ray spectral analysis to explain these questions; study was done of the irregularity of mechanical properties, and the uniform and concentrated deformation was determined. Metallographic analysis showed that the rods of three batches with an aluminum content of less than 5% have a polyhedral structure. With an aluminum content of approximately 5% and above, the "regularity" of the grain forms is destroyed and the overall

TABLE 2. MECHANICAL PROPERTIES OF TITANIUM ALLOYS.

| Alloy Composition, % | $\sigma_b$, kgf/mm$^2$ | $\sigma_{0.2}$, kgf/mm$^2$ | $\delta$, % | $\psi$, % |
|---|---|---|---|---|
| Industrial titanium | 35.1 | 20.7 | 50.3 | 75.7 |
| 1.6 Al | 48.0 | 32.3 | 18.9 | 34.8 |
| 5 Zr | 42.0 | 33.1 | 47.5 | 78.3 |
| 4 Sn | 41.3 | 33.1 | 36.6 | 66.0 |
| 1 V | 40.7 | 32.9 | 45.5 | 80.6 |

TABLE 3. MECHANICAL PROPERTIES OF TITANIUM ALLOYS.

| Alloy Composition, % | $\sigma_b$, kgf/mm$^2$ | $\sigma_{0.2}$, kgf/mm$^2$ | $\delta$, % | $\psi$, % | Deflection value of a plate when tested for static depression, mm |
|---|---|---|---|---|---|
| 3.42 Al | 65.3 | 49.4 | 12.7 | 30.6 | 10 |
| Cold-worked titanium | 57.5 | 52.5 | 10.0 | 56.7 | 22 |

microstructure becomes qualitatively different from the microstructure of less alloyed alloys. The electric resistance (Fig. 1, c) increases almost in a straight line when up to 4% of aluminum is introduced. With 4-5%, there is a slight reduction of electric resistance; with a further increase of aluminum, the growth of electric resistance slows down. Research into the distribution of aluminum in the structure of alloys carried out with a microradiographic instrument with a localization of 1 μm showed that with an average content of aluminum of 3.42%, its local concentration inside grains is 3.22%, and near the boundaries, 10.6%. In an alloy with a 5.75% content of aluminum, individual sections /112
were detected with a concentration of 5.43 and 9.14%, and with an 8% content of Al -- 8.37 and 9.12%. Comparison of this information shows that the irregularity of distribution of aluminum is at a minimum in an alloy with 8% Al.

The irregularity of mechanical properties was estimated according to a method [10] by mass determination of microhardness on sections by calculating the root-mean-square hardness deviation (dispersion). The value of dispersion was determined according to formula:

$$\sigma_m = \sqrt{\frac{\sum_{i=1}^{i=m} (H_{med} - H_i)^2}{n-1}},$$

where n is the overall number of measurements; m is the number of measurements of hardness; $H_{med}$ is the medium hardness.

It follows from the information below that the value of dispersion when adding 3.93% Al to titanium increases approximately 2.5 times.

| | | | | | |
|---|---|---|---|---|---|
| Aluminum content, % | 0 | 1.6 | 3.93 | 5.32 | 7.84 |
| $H_{med}$, $kgf/mm^2$ | 126.2 | 163.6 | 166.3 | 236.4 | 243.0 |
| $\sigma_m$ | 21 | 40.2 | 59.2 | 33.8 | 27.5 |

With a further increase of aluminum content to 7.84%, the value of $\sigma_m$ again begins to decrease, which shows a greater regularity of alloy properties containing 7.32 and 7.84% Al. The dispersion value of alloy hardness with 7.8% Al is close to that for pure titanium.

The final stage of investigations was the study of the regular and concentrated amount of deformation during expansion. Figure 1, d, shows that the uniform contraction of titanium decreases sharply when up to 5% aluminum is added (approximately three times). With an aluminum content of approximately 8%, the uniform deformation somewhat increases, and with an increase of aluminum content to 9-10% is again reduced to almost zero. The value of the concentrated deformation of titanium, as the uniform one, is reduced intensely when alloyed with up to 5% aluminum. The concentrated contraction of an alloy with an aluminum content of approximately 5% is three times less than that of an industrial titanium, and more than half as much as a titanium alloy with 2% Al. When the aluminum content is increased from 5 to 8%, the value of the concentrated contraction decreases by approximately 1.5 times, and alloy specimens with a greater concentration of aluminum disintegrate almost without concentrated deformation.

According to the latest research into the uniform condition diagram of Ti-Al [8, 9], aluminum in a quantity from 0 to 7.5% is in an α-solid solution; in a concentration interval from 7.5 to 14% extends over a two-phase range ($\alpha + \alpha_2$), where the $\alpha_2$-phase is a solid solution of aluminum based on a $Ti_3Al$ compound with an ordered hexagonal structure [8].

The information obtained -- the recurvature on the electric resistance curve, the qualitative change of microstructure, the recurvature on concentration curves of mechanical properties -- shows that the violation of homogeneity of the solid solution occurs when the aluminum content is approximately 5% (9 technical atmospheres-%). This agrees with data from works [4, 7], where a second phase was detected with this aluminum content. Judging by the results of local spectral analysis, the distribution of aluminum, even in low-alloyed alloys, is nonuniform, and the aluminum concentration in individual microvolumes reaches values sufficient for the formation of a second phase (up to 9-10%). /113
A possible reason for this concentration nonuniformity is the redistribution of aluminum between the α- and the β-phases when there is sufficiently slow quenching from the β-phase in the $\beta \rightarrow \alpha + \beta \rightarrow \alpha$-transformation process. The possibility for this distribution of aluminum was shown by Hall [11] in conformity with a two-phase titanium alloy with 6% Al and 4% V.

The distribution of α-stabilizing elements in the $\beta \rightarrow \alpha + \beta \rightarrow \alpha$-transformation process is extremely nonuniform. The degree of chemical nonuniformity and measurements of microvolumes with an aluminum content above average should increase as the concentration of aluminum in alloys increases, since, apart from increasing the aluminum content, the temperature interval of the two-phase $\alpha + \beta$-region is enlarged. Apparently, with an average aluminum content of approximately 5%, the second phase forms in amounts and sizes sufficient to change the physical properties and structure of the alloy. The presence of second-phase segregations, even in low-alloyed Ti-Al alloys, causes a nonuniformity in which deformation takes place. It is known that the value of concentrated deformation depends directly on the tendency of the material to form defects. Therefore, when introducing aluminum, the amount of concentrated contraction sharply decreases. In the light of this information, the intensive increase of strength properties occurs, apparently, not only as the result of elastic distortions, brought by aluminum atoms into titanium's crystal lattice, but also due to second-phase segregations. The increase of aluminum content from 2 to 5% causes relatively little change in deformation, compared with those radical changes which occur during a transition from unalloyed titanium to low-alloyed alloys. Therefore, plasticity-composition curves in this concentration interval are reduced less than in small concentrations. The results of micro-x-ray spectral analysis and the change of the root-mean-square deviation in hardness show a more uniform distribution of aluminum in a titanium alloy with 8% Al. Therefore, apparently, plastic deformation of this alloy takes place more uniformly, and this leads to an increase of the final plastic characteristics of the alloy. The absence of plasticity increase in a titanium alloy with 8% Al in works between 1951 and 1963 [1, 2, 4, 5] can be explained by the fact that sponge, used in these years, contained a considerably greater amount of interstitial impurities which could cause a sharper decrease of plasticity than when alloying with aluminum.

It can be assumed that tin and zirconium, which are very weak β-stabilizers, and which dissolve almost identically in the α- and β-phases, or vanadium, which, in an amount of up to ∿ 2.5% dissolves in the α-phase, are distributed more uniformly among α- and β-phase plates than aluminum, the solubility of which in the β-phase in the two-phase region interval is minute [12]. As a result of this, the effect of these elements on the plasticity characteristics of unalloyed titanium is considerably less than those of aluminum. It must be remembered that the amount of relative elongation for unalloyed titanium (and in respect to this, the amount of its reduction when aluminum is introduced) depends considerably on the size of the pure titanium grain (Table 4). /114

TABLE 4. THE EFFECT OF GRAIN SIZE ON MECHANICAL PROPERTIES OF TITANIUM ALLOYS.

| Alloy Composition, % | Grain Size, mm | Mechanical Properties | | | |
|---|---|---|---|---|---|
| | | $\sigma_b$, kgf/mm$^2$ | $\sigma_{0.2}$, kgf/mm$^2$ | δ, % | ψ, % |
| Unalloyed titanium<br>1.73 Al | 0.02—0.04 | 35.0<br>46.3 | 20.4<br>31.6 | 35.2<br>26.1 | 74.3<br>48.3 |
| —<br>1.60 Al | 0.4—0.8 | 20.7<br>32.3 | 20.7<br>32.3 | 49.6<br>18.9 | 71.3<br>37.8 |

The dependence of plasticity characteristics of unalloyed titanium, and the amount in which they are reduced when aluminum is added, on the grain size can be explained in the light of work [13], where it is shown that in α-titanium alloys with a large grain, apart from shear deformation, twinning also takes place. To a great extent, the introduction of aluminum eliminates the possibility of twinning in titanium. Therefore, it is seen that the addition of aluminum to industrial titanium with a small grain, where twinning is to some extent forbidden, will have less effect than on specimens with a coarse-grained structure.

## Conclusions

1. It was found that when producing semifinished products in actual production conditions, the main alloying element of titanium alloys, aluminum, is distributed ununiformly in the alloy structure since it dissolves mainly in the α-phase when there is relatively slow quenching of alloys in a two-phase region in the $\beta \to \alpha + \beta \to \alpha$-transformation process.

2. Due to microinhomogeneity of aluminum distribution, its concentration in individual microvolumes, even in low-alloy α-alloys (~2% Al), can be sufficient for forming a second phase ($\alpha_2$), although in accordance with the equilibrium state diagram, the $\alpha_2$-phase only occurs when there is a 7.5% content of aluminum.

3. Apparently, the significant change in the mechanical properties of titanium and α-alloys occurs when aluminum is introduced, not only due to elastic distortions, introduced by aluminum atoms into the titanium lattice, but by the appearance of a second phase. The inhomogeneity of distribution of aluminum is very strong and is not removed during prolonged homogenizing annealing.

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